



LBNF/DUNE
and the Hunt
for Leptonic
CP Violation

Mary Bishai
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National Lab

Introduction
CP in ν SM
CPV and other
New Physics

Current
Experimental
Landscape

LBNF/DUNE

Conclusion

LBNF/DUNE and the Hunt for Leptonic CP Violation

FPCP 2016, 6-9 June 2016, Caltech

Mary Bishai
Brookhaven National Lab

June 8, 2016

Outline

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- CPV and other New Physics

2 Current Experimental Landscape

3 LBNF/DUNE

4 Conclusion

CP Violation in PMNS and CKM

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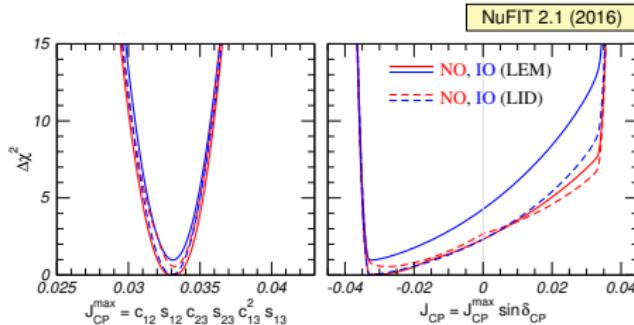
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In 3-flavor mixing the degree of CP violation is determined by the Jarlskog invariant:

$$J_{CP}^{\text{PMNS}} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \delta_{CP}.$$



(JHEP 11 (2014) 052, arXiv:1409.5439)

Given the current best-fit values of the ν mixing angles :

$$J_{CP}^{\text{PMNS}} \approx 3 \times 10^{-2} \sin \delta_{CP}.$$

For CKM:

$$J_{CP}^{\text{CKM}} \approx 3 \times 10^{-5},$$

despite the large value of $\delta_{CP}^{\text{CKM}} \approx 70^\circ$.

$\nu_\mu \rightarrow \nu_e$ Oscillations in the 3-flavor ν SM

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In the ν 3-flavor model matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations (or vice versa). With terms up to second order in $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2 = 0.03$ and $\sin^2 \theta_{13} = 0.02$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin \delta}}_{\text{CP violating}} + \underbrace{P_{\cos \delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where for oscillations in vacuum:

$$P_0 = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta),$$

$$P_{\sin \delta} = \alpha 8J_{cp} \sin^3(\Delta),$$

$$P_{\cos \delta} = \alpha 8J_{cp} \cot \delta_{CP} \cos \Delta \sin^2(\Delta),$$

$$P_3 = \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2(\Delta),$$

and where

$$\Delta = \Delta m_{31}^2 L / 4E$$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $P_{\sin \delta} \rightarrow -P_{\sin \delta}$

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where for oscillations in matter with constant density:

$$P_0 = \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A - 1)^2} \sin^2[(A - 1)\Delta],$$

$$P_{\sin \delta} = \alpha \frac{8J_{cp}}{A(1 - A)} \sin \Delta \sin(A\Delta) \sin[(1 - A)\Delta],$$

$$P_{\cos \delta} = \alpha \frac{8J_{cp} \cot \delta_{CP}}{A(1 - A)} \cos \Delta \sin(A\Delta) \sin[(1 - A)\Delta],$$

$$P_3 = \alpha^2 \cos^2 \theta_{23} \frac{\sin^2 2\theta_{12}}{A^2} \sin^2(A\Delta),$$

and where

$$\Delta = \Delta m_{31}^2 L / 4E \quad \text{and} \quad A = \sqrt{2} G_F N_e 2E / \Delta m_{31}^2.$$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $P_{\sin \delta} \rightarrow -P_{\sin \delta}$

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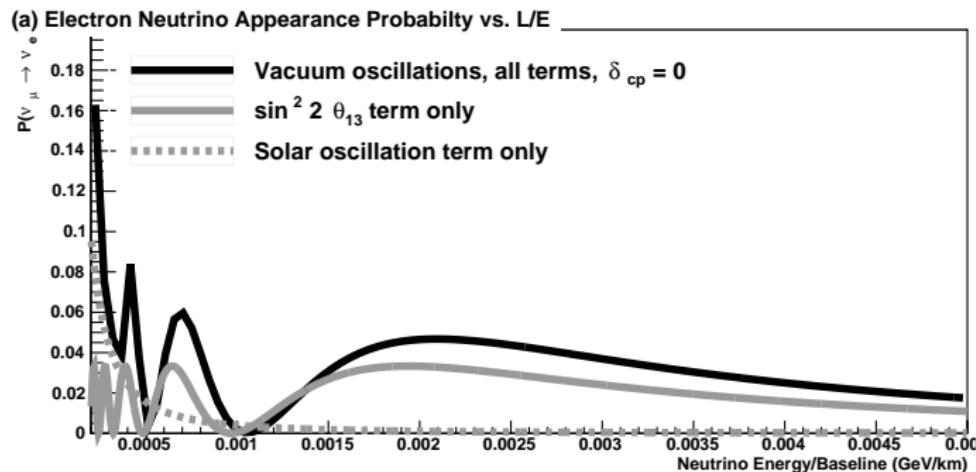
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The $\nu_\mu \rightarrow \nu_e$ probability maxima due to the atmospheric oscillation scale occur at

$$\frac{L \text{ (km)}}{E_n \text{ (GeV)}} = \left(\frac{\pi}{2} \right) \frac{(2n - 1)}{1.27 \times \Delta m_{31}^2 \text{ (eV}^2\text{)}} \approx (2n - 1) \times \frac{515 \text{ km}}{\text{GeV}}$$



$\nu_\mu \rightarrow \nu_e$ Oscillations in the 3-flavor ν SM

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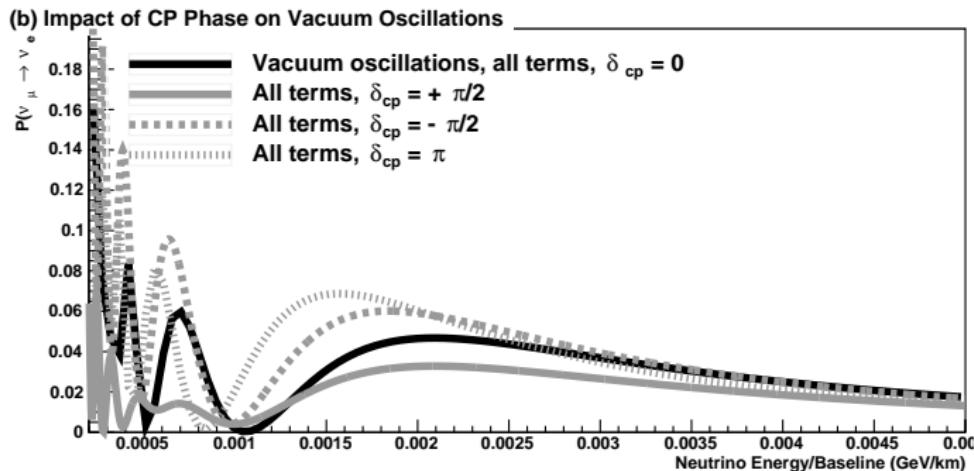
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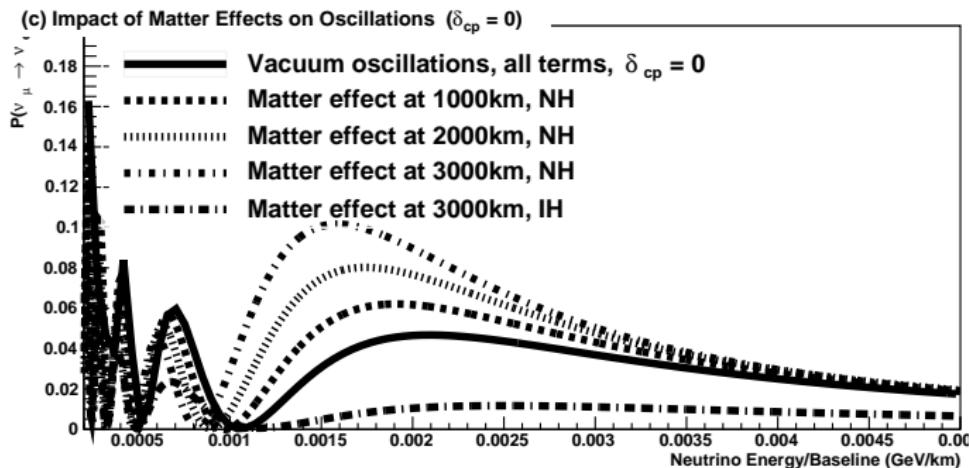
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Impact of Sterile Neutrinos on Long-Baseline ν Oscillations

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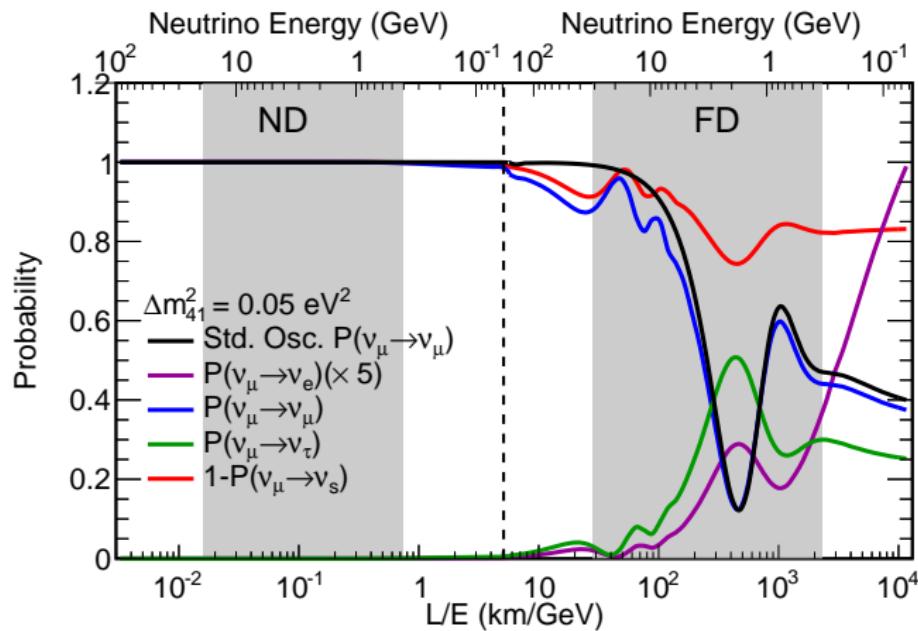
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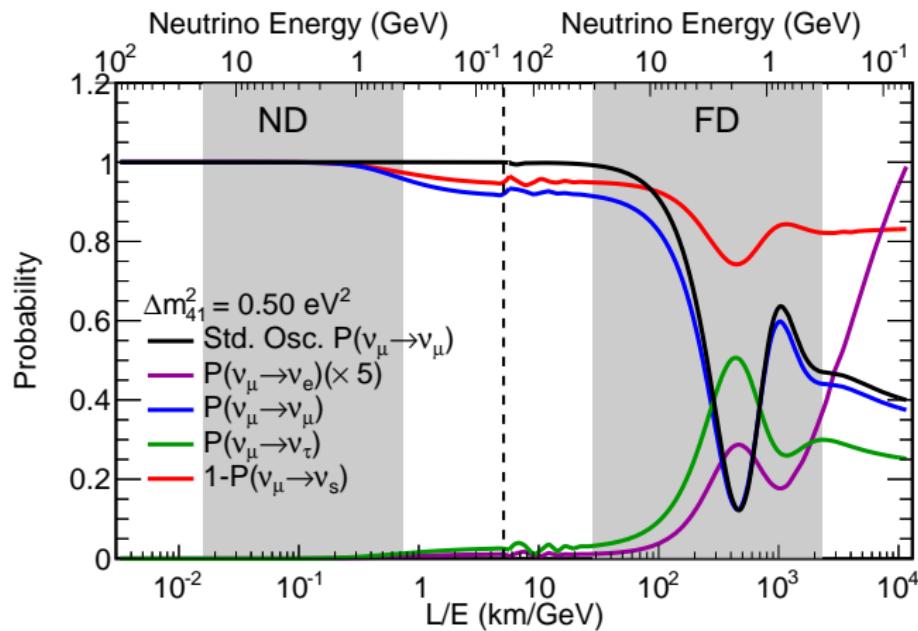
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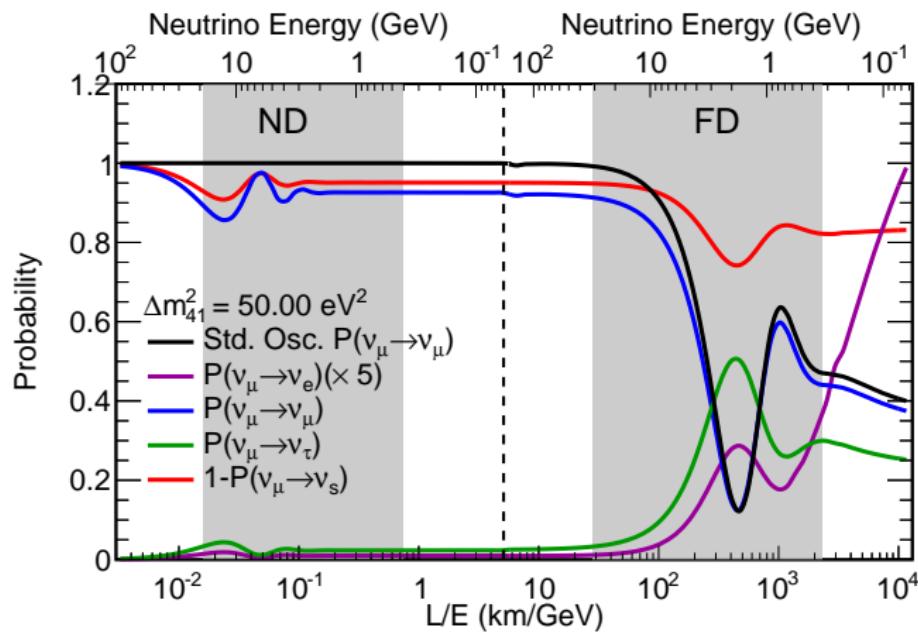
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CP Violation in ν SM

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The charge-parity (CP) asymmetry is defined as

$$\mathcal{A}_{cp} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

$$\mathcal{A}_{cp} \sim \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta}{\sin \theta_{23} \sin \theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects}$$

W. Marciano, Z. Parsa, Nucl.Phys.Proc.Suppl. 221 (2011)

The CP phase δ_{cp} is unknown. CP is violated when $\delta_{cp} \neq 0, \pi$

The 4 most important things to know about ν CPV

- $\mathcal{A}_{cp} \propto 1/\sin \theta_{13} \Rightarrow$ Large θ_{13} makes CPV searches HARDER.
- $\mathcal{A}_{cp} \propto 1/\tan \theta_{23} \Rightarrow$ Large $\sin(\theta_{23}) =$ smaller CPV (octant!)
- $\mathcal{A}_{cp} \propto 1/E_\nu \Rightarrow$ CP asymmetries are larger at lower energies
- $\mathcal{A}_{cp} \propto L \Rightarrow$ CP asymmetries are larger at longer baselines

CP Asymmetry 3-flavor and with a Sterile Neutrino

$$\Delta m_{41}^2 \sim 1 \text{ eV}^2$$

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The integrated CP asymmetry at the DUNE/LBNF baseline of 1300km :

Red: 3+0

Blue: 3+1

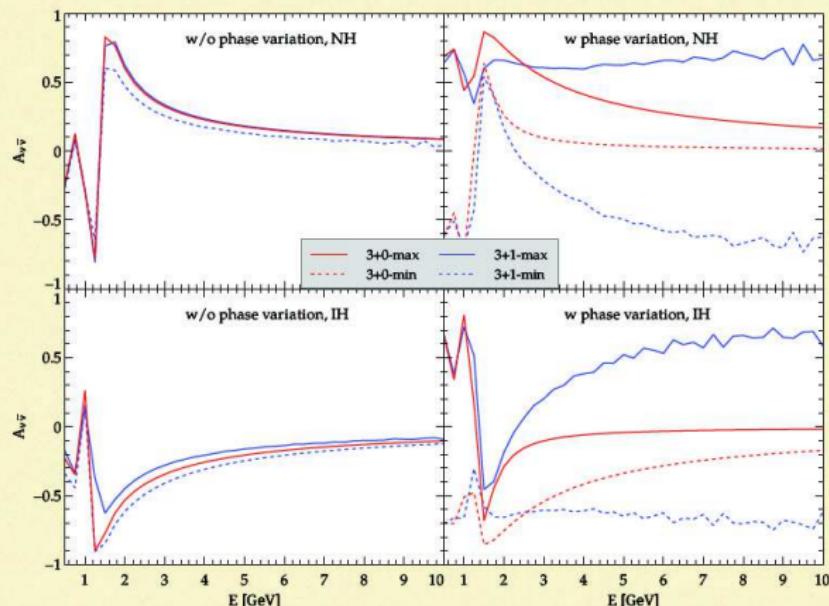
Left panels: all
phases zero

Rt. panels: all
phases running

Solid: Max
intergrated
asymm

Dashed: Min
intergrated
asymm

Top : NH
Bottom: IH



(D. Dutta et. al. JHEP 1511 (2015) 039; arXiv:1508.06275)

Observation of a CP asymmetry is not sufficient to determine its origin.

Non-Standard Interactions and CP Asymmetries

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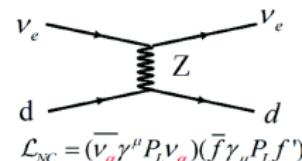
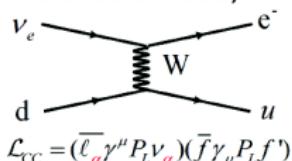
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- In the Standard Model,



- With new physics, we could have

$$\mathcal{L}_{CC} = (\bar{\ell}_a \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_{L,R} f')$$



**CC NSI
production, detection**

$$\mathcal{L}_{NC} = (\bar{\nu}_a \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_{L,R} f')$$



**NC NSI
propagation**

$$H = U \begin{pmatrix} 0 & \Delta m_{21}^2 / 2E & \\ & \Delta m_{31}^2 / 2E & \end{pmatrix} U^\dagger + \tilde{V}_{MSW}$$

$$\tilde{V}_{MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m \\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m \end{pmatrix}$$

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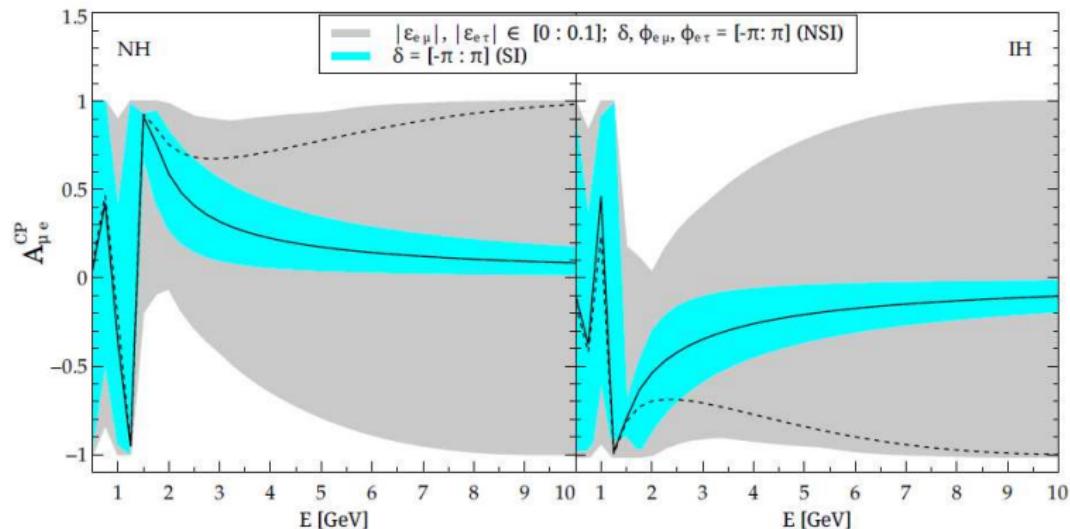
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NSI could also impact CPV interpretation in long-baseline:



(M. Masud, A. Chatterjee, P. Mehta arXiv:1510.08261)

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Results from Current $\nu_\mu \rightarrow \nu_e$ Long-Baseline Experiments and Near Future

$\nu_\mu \rightarrow \nu_e$ Event Rates - Various Experiments.

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arXiv:1307.7335, for 50 kton.years* of exposure. No detector effects

Experiment	Baseline	Super Beams		
		$\nu_\mu \rightarrow \nu_\mu$	$\nu_\mu \rightarrow \nu_\tau$	$\nu_\mu \rightarrow \nu_e$ δ_{CP} range
T2K	295km (off-axis)			
30 GeV, 750 kW				
9×10^{20} POT/year		900	< 1	40 - 70
MINOS LE	735km			
120 GeV, 700 kW				
6×10^{20} POT/year		11,000	115	230-340
NO ν A	810km (off-axis)			
120 GeV, 700 kW				
6×10^{20} POT/year		1500	10	120 - 200
LBNF LE [†]	1,300km			
80 GeV, 1.1MW				
1.5×10^{21} POT/year		4300	160	350 - 600
LBNF ME [†]	1,300km			
120 GeV, 1.2MW				
1.1×10^{21} POT/year		12,000	690	290 - 430

* Facility duty factor taken into consideration

† 2012 LBNE CDR Reference Design with NuMI style focusing

Even with maximal CP, event rate is a ≤ 10 $\nu_\mu \rightarrow \nu_e$ per kT.MW.yr

Experimental challenge for CPV measurements: STATISTICS!

First $\nu_\mu \rightarrow \nu_e$ results from T2K and NO ν A

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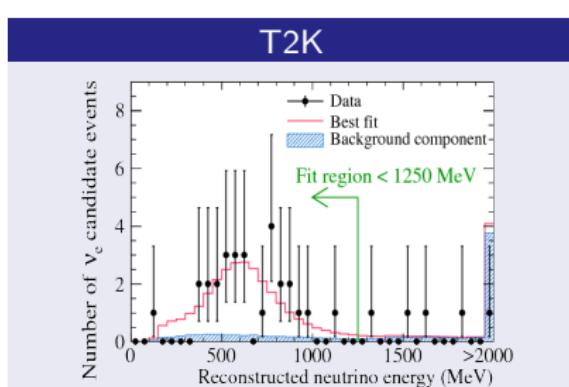
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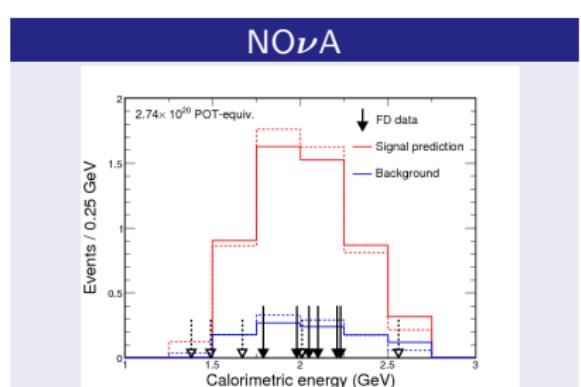
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6.57×10^{20} POT in ν mode:
28 ν_e candidates (4.9 ± 0.6 bkgd)
 4.04×10^{20} POT in $\bar{\nu}$ mode:
3 $\bar{\nu}_e$ candidates (1.51 to 1.77 bkgd).



2.74×10^{20} POT in ν mode:
6 LID candidates
(3.3σ signal of ν_e appearance)
11 LEM candidates
(5.5σ signal of ν_e appearance)
No $\bar{\nu}$ running yet!

The current results favor maximal CP at NH

T2K+NO ν A Prospects

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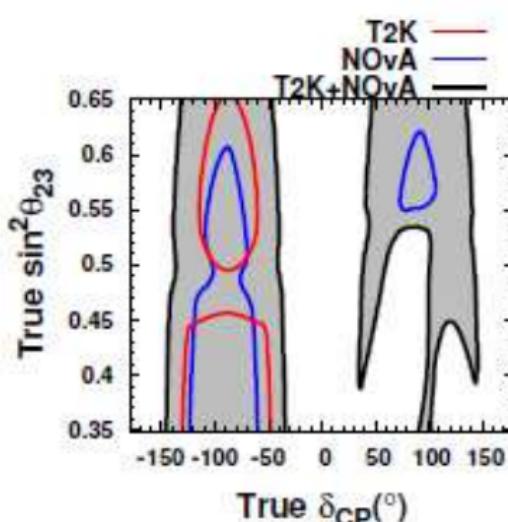
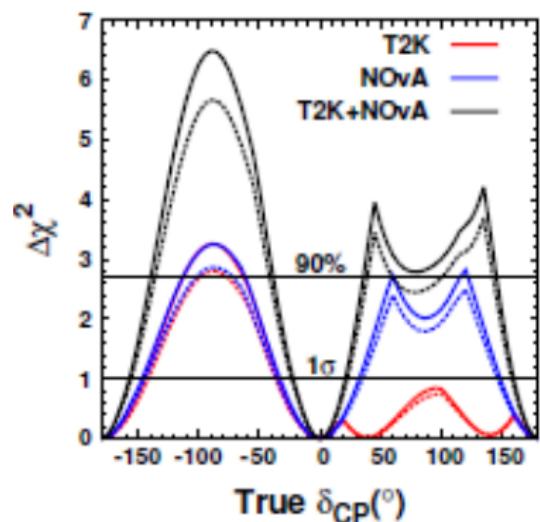
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**T2K (7.8×10^{21} POT) and NO ν A (1.8×10^{21} POT) combined,
exclusion of $\delta_{cp} = 0$ at 90% C.L.** (K. Abe et. al.PTEP 2015 (2015) no.4, 043C01;
arXiv:1409.7469):

Normal Hierarchy



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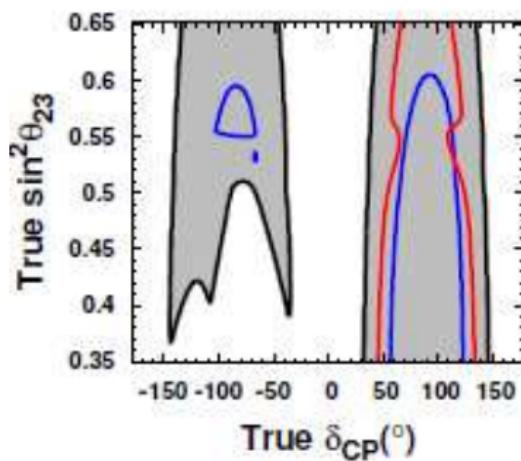
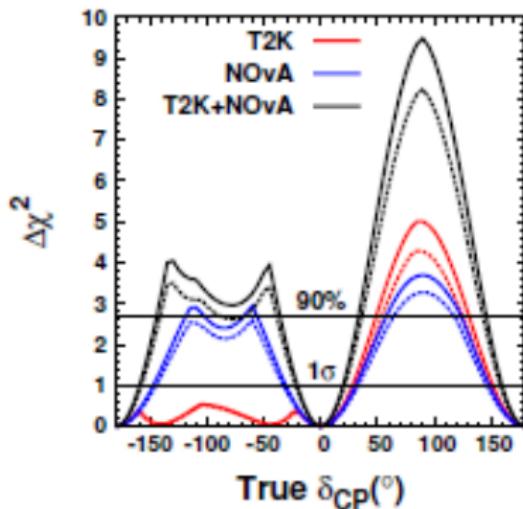
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arXiv:1409.7469):

Inverted Hierarchy



Long Baseline ν Facility (LBNF) and Deep Underground ν Experiment (DUNE)

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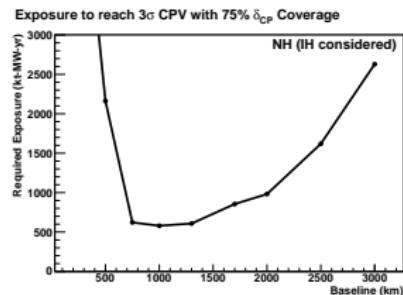
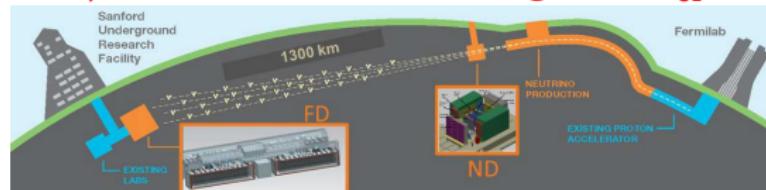
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GOAL: Precision measurements of the parameters that govern
 $\nu_\mu \rightarrow \nu_x$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_x$ to determine δ_{CP} , sign of Δm^2_{31} , octant of θ_{23} .



- Long baseline experiment with a tunable wide-band beam and a 1300km baseline from Fermilab to the Sanford Underground Research Facility in Lead, SD.

M. Bass et. al. Phys.Rev. D91 (2015) 052015

- Highly capable multi-purpose Near Detector at Fermilab
- 40 kton fiducial Liquid Argon TPC Far Detector (80 kton total). Both single and dual-phase LArTPC options under consideration.

The DUNE Collaboration

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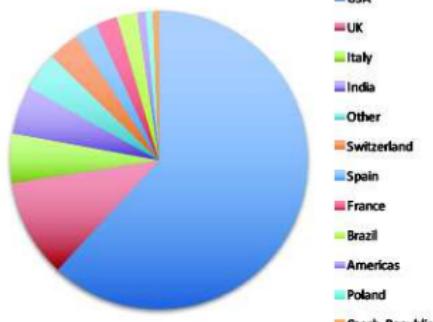
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Formed in Jan 2015 from combination of the US-based LBNE and LBNO experiments.



856 Collaborators

from 149 Institutions in
29 Nations



Armenia, Belgium, Brazil,
Bulgaria, Canada, Colombia,
Czech Republic, Finland,
France, Greece, India, Iran,
Italy, Japan, Madagascar,
Mexico, Netherlands, Peru,
Poland, Romania, Russia,
Spain, Sweden, Switzerland,
Turkey, UK, USA, Ukraine

Fermilab Accelerator upgrades for DUNE

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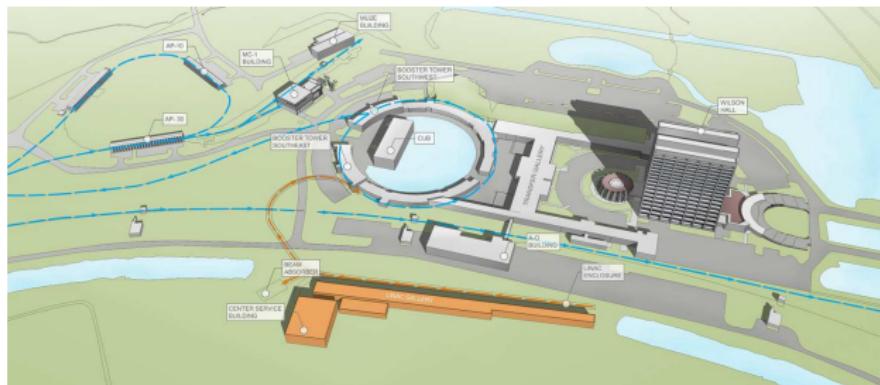
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Planned upgrades to the Fermilab complex to increase proton intensity:



PIP-II replaces upstream portion of linac feeding into 8 GeV Booster:
1.03 MW at 60 GeV
1.07 MW at 80 GeV
1.20 MW at 120 GeV

Ready by 2025

Further upgrades (PIP-III) would replace booster with Rapid Cycling Synchrotron (RCS) or SC Linac.
Currently in R&D stage.

$\geq 2.0 \text{ MW at } 60 \text{ GeV}$
 $\geq 2.3 \text{ MW at } 120 \text{ GeV}$

The LBNF Beamlne for DUNE

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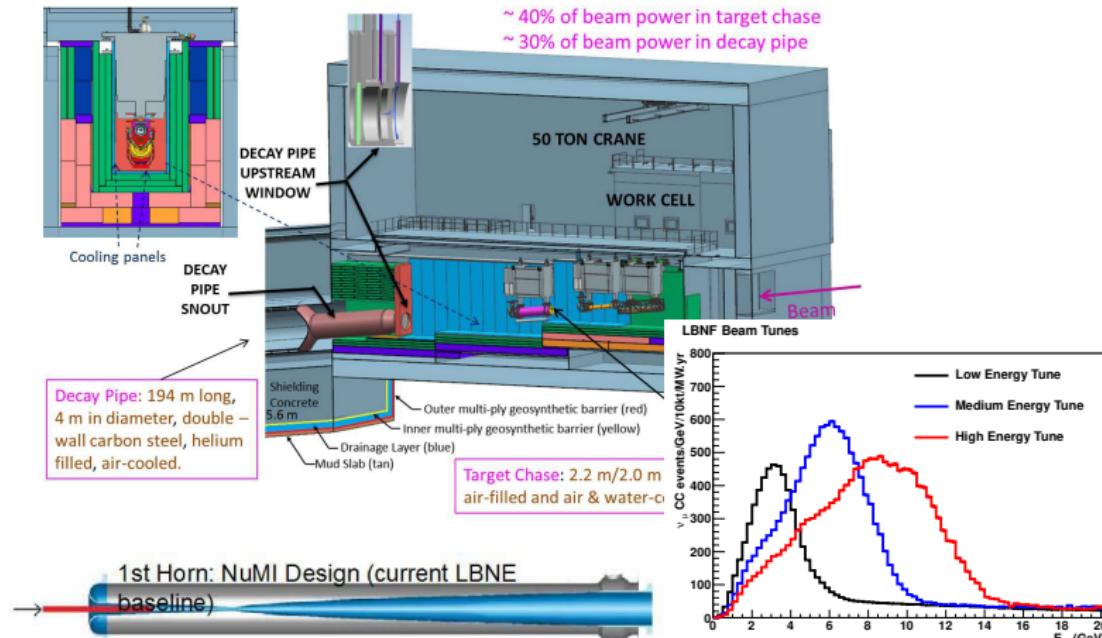
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Advanced conceptual design *tunable wide-band* NuMI-style focusing:



Optimized focusing design using genetic algorithm with 3 horns

~ 30% more flux for CPV

The DUNE Near Detector Reference Design

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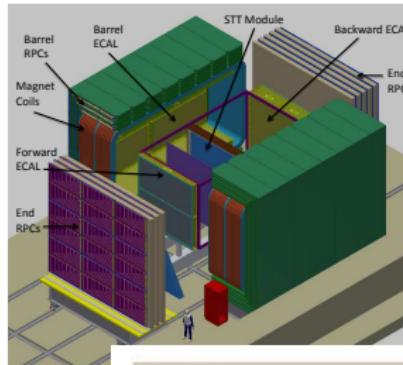
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Reference design is the Fine Grained Tracker based on the “LBNE-India Detailed Project Report (DPR)” submitted to DAE, India in 2012. Alternative/additional designs under consideration by DUNE



Performance Metric	Value
Vertex resolution	0.1 mm
Angular resolution	2 mrad
E_e resolution	5%
E_μ resolution	5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
NC π^0 /CCe rejection	0.1%
NC γ /CCe rejection	0.2%
NC μ /CCe rejection	0.01%

Parameter	Value
STT detector volume	$3 \times 3 \times 7.04 \text{ m}^3$
STT detector mass	8 tons
Number of straws in STT	123,904
Inner magnetic volume	$4.5 \times 4.5 \times 8.0 \text{ m}^3$
Targets	1.27-cm thick argon ($\sim 50 \text{ kg}$), water and others
Transition radiation radiators	2.5 cm thick
ECAL X_0	10 barrel, 10 backward, 18 forward
Number of scintillator bars in ECAL	32,320
Dipole magnet	2.4-MW power; 60-cm steel thickness
Magnetic field and uniformity	0.4 T; < 2% variation over inner volume
MuID configuration	32 RPC planes interspersed between 20-cm thick layers of steel

Measuring the ν Flux with the DUNE ND

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Technique	Flavor	Absolute normalization	Relative flux $\Phi(E_\nu)$	Near Detector requirements
NC Scattering $\nu_\mu e^- \rightarrow \nu_\mu e^-$	ν_μ	2.5%	$\sim 5\%$	e ID θ_e Resolution e^-/e^+ Separation
Inverse muon decay $\nu_\mu e^- \rightarrow \mu^- \nu_e$	ν_μ	3%		μ ID θ_μ Resolution 2-Track ($\mu + X$) Resolution μ energy scale
CC QE $\nu_\mu n \rightarrow \mu^- p$ $Q^2 \rightarrow 0$	ν_μ	3 – 5%	5 – 10%	D target p Angular resolution p energy resolution Back-Subtraction
CC QE $\overline{\nu}_\mu p \rightarrow \mu^+ n$ $Q^2 \rightarrow 0$	$\overline{\nu}_\mu$	5%	10%	H target Back-Subtraction
Low- ν_0	ν_μ		2.0%	μ^- vs μ^+ E_μ -Scale Low- E_{Had} Resolution
Low- ν_0	$\overline{\nu}_\mu$		2.0%	μ^- vs μ^+ E_μ -Scale Low- E_{Had} Resolution
Low- ν_0	$\nu_e/\overline{\nu}_e$	1-3%	2.0%	e^-/e^+ Separation (K_L^0)
CC	ν_e/ν_μ	<1%	$\sim 2\%$	e^- ID & μ^- ID p_e/p_μ Resolution
CC	$\overline{\nu}_e/\overline{\nu}_\mu$	<1%	$\sim 2\%$	e^+ ID & μ^+ ID p_e/p_μ Resolution
Low- ν_0 /CohPi	$\overline{\nu}_\mu/\nu_\mu$	$\sim 2\%$	$\sim 2\%$	μ^+ ID & μ^- ID p_μ Resolution Low- E_{Had} Resolution

Near to Far Extrapolation

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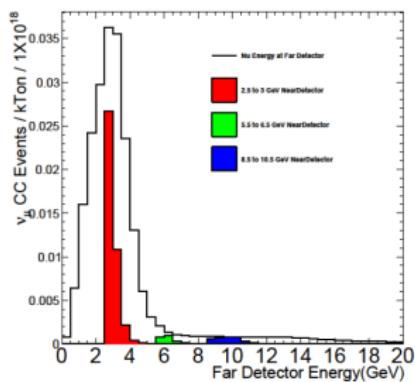
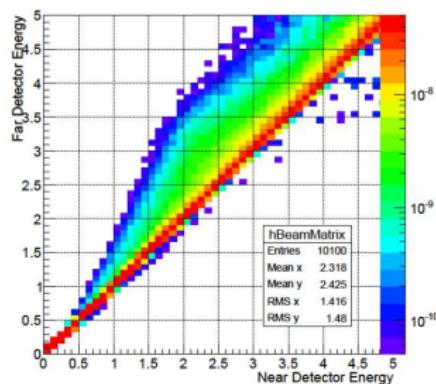
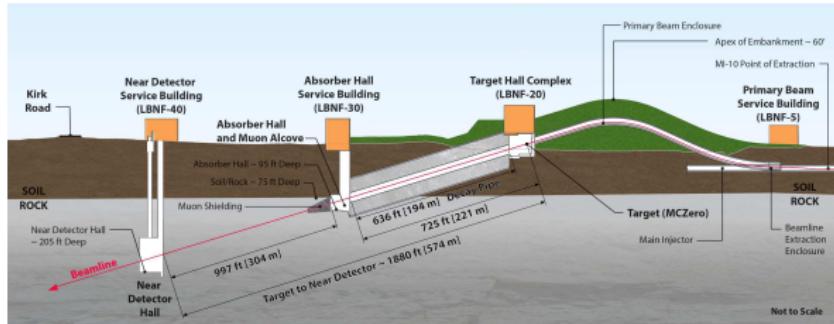
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Extrapolation from ND (574m) to FD (1297km) is not trivial!

The DUNE Far Detector LArTPC

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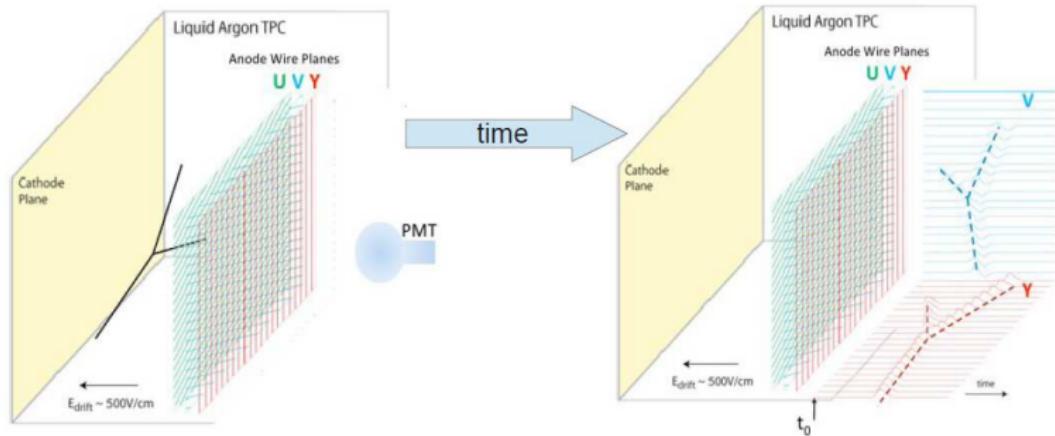
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Liquid Argon TPCs: Single Phase



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Liquid Argon TPCs: Dual Phase

4.) Charge collection on a 2D anode readout

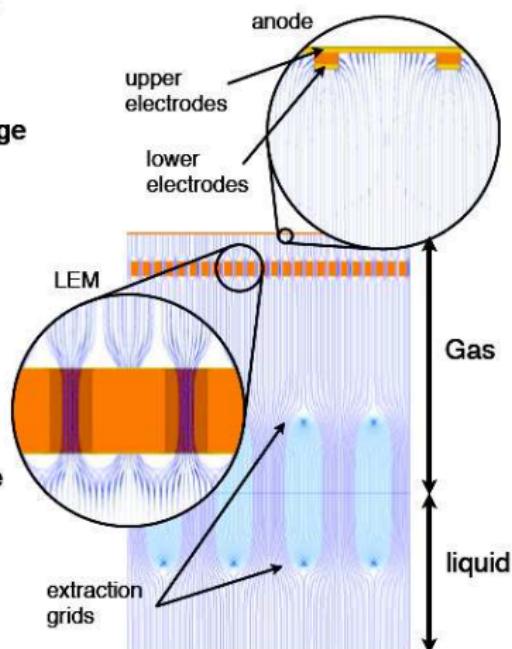
(symmetric unipolar signals with two
orthogonal views)

3.) Charge multiplication in the holes of the Large Electron Multiplier (LEM)



2.) Drift electrons are efficiently emitted into the gas phase

1.) Ionization electrons drift towards the liquid argon surface



The DUNE Far Detector LArTPC

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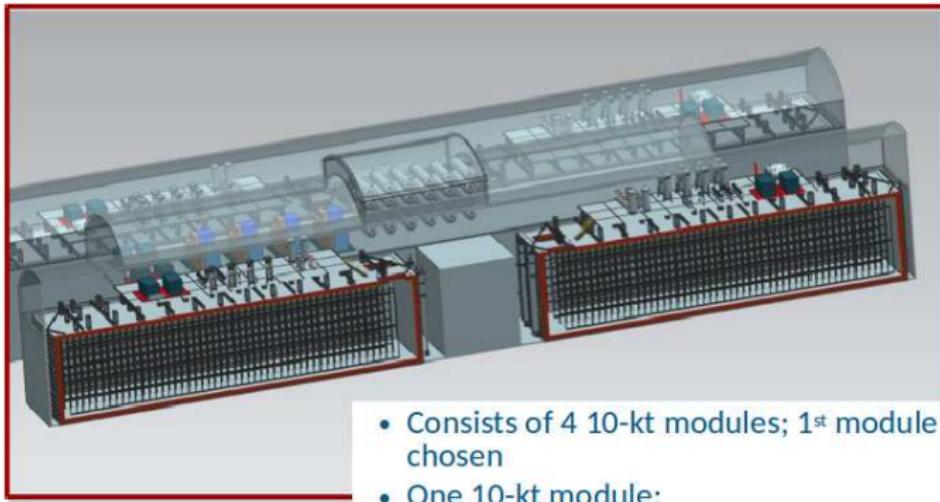
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- Consists of 4 10-kt modules; 1st module design chosen
- One 10-kt module:
 - Active volume 12m x 14.5m x 58m
 - 150 total APAs; 384,000 sense wires
- Each APA: 2.3m x 6m; 2560 sense wires
- 3 sense wire planes; wire pitch: ~5 mm
- Drift field: 500 V/cm
- Maximum drift distance: 3.6 m (~2 ms)

Simulation/Reconstruction in a Single Phase LArTPC (<http://www.phy.bnl.gov/wire-cell>)

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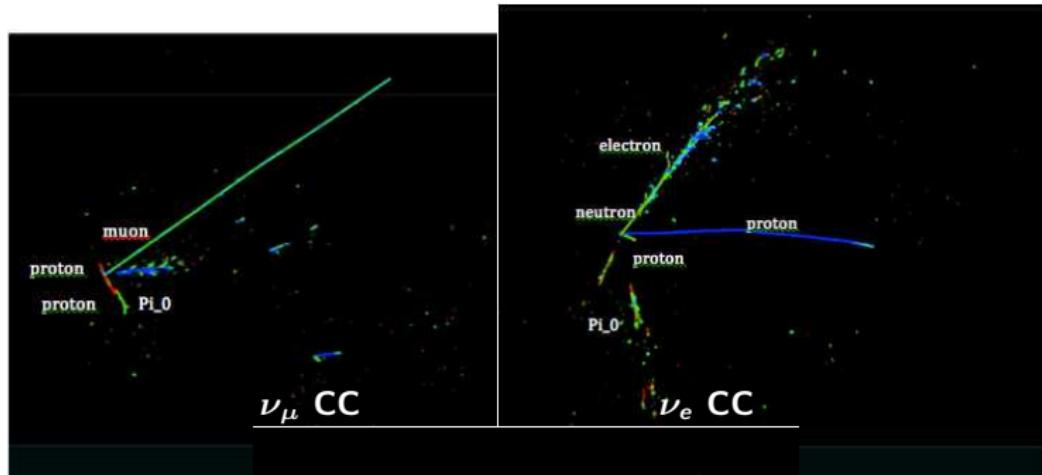
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DUNE Event Spectra

Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr = 1×10^{21}

p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085$, $\sin^2 \theta_{23} = 0.45$, $\delta m_{31}^2 = 2.46 \times 10^{-3}$ eV 2)

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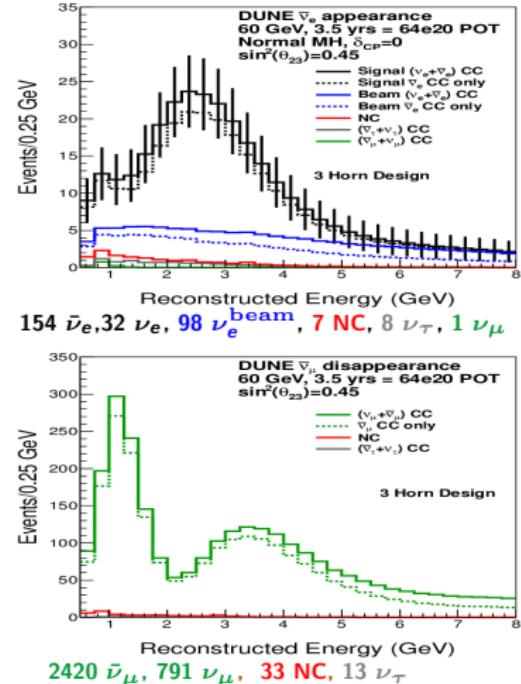
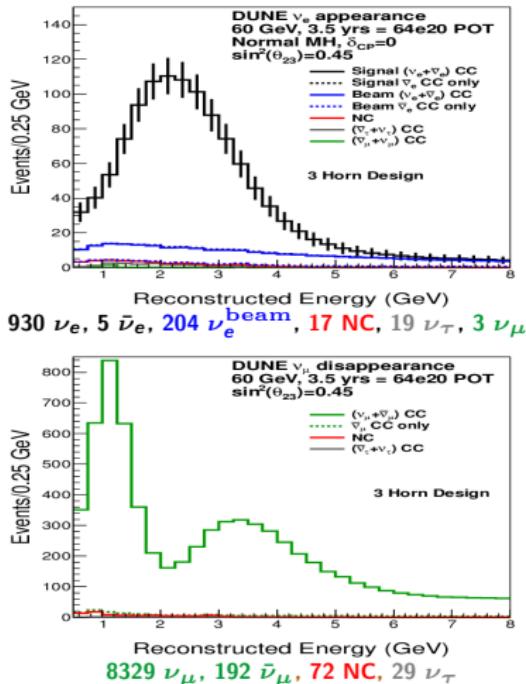
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Simultaneous fit to all four samples to determine osc. params

DUNE Event Spectra

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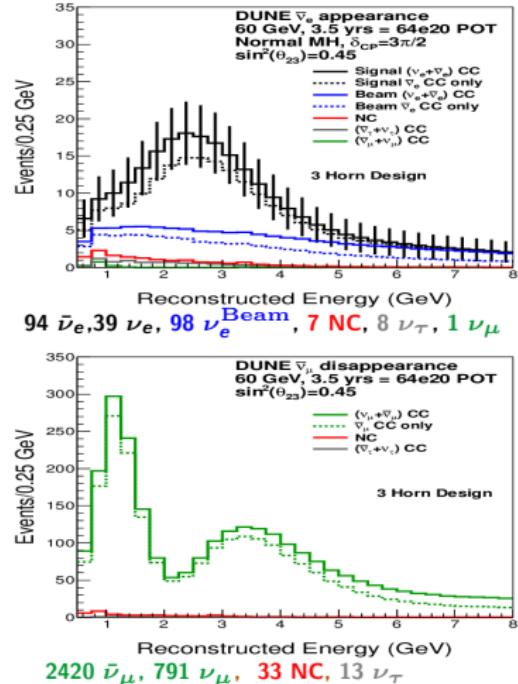
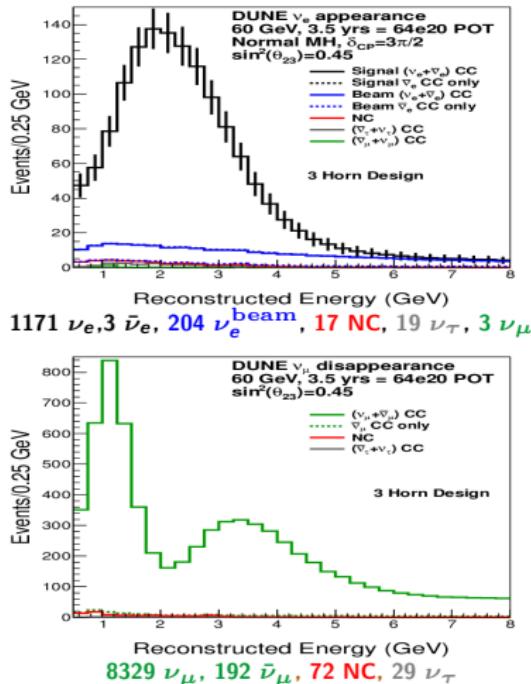
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DUNE CP Sensitivity

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Source of Uncertainty	MINOS ν_e	T2K ν_e	Goal for DUNE ν_e
Beam Flux	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	~2%
Energy Scale (ν_μ)	3.5%	Included above	Included in 5% ν_μ uncertainty
Energy Scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial Volume	2.4%	1%	1%
Total Uncertainty	5.7%	6.8%	3.6%
Used in DUNE sensitivity calculations:			5% \oplus 2%

DUNE CP Sensitivity

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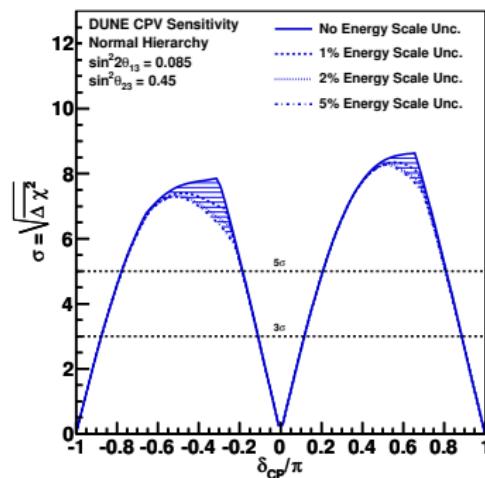
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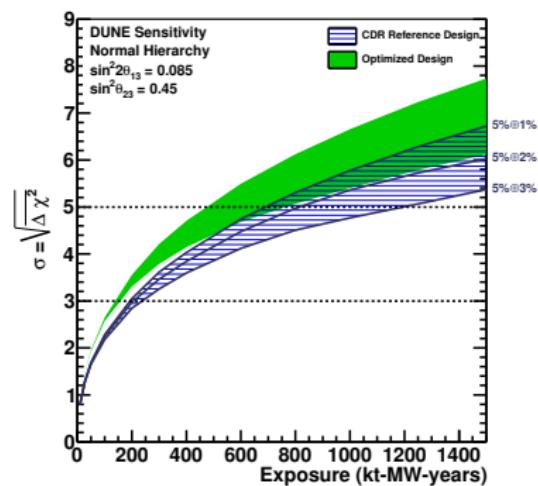
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With $550 \text{ kT.MW.yr} \geq 5\sigma$ sensitivity for 50% δ_{cp}
With $850 \text{ kT.MW.yr} \geq 3\sigma$ sensitivity for 75% δ_{cp}

CP Violation Sensitivity



50% CP Violation Sensitivity



DUNE Physics Milestones (NH)

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Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\text{CP}} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\text{CP}} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\text{CP}} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\text{CP}} = 0$)	450	290
CPV at 5σ ($\delta_{\text{CP}} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

Even if CP is maximally violated → several years to 5σ discovery

Sensitivity to $B\nu$ SM Physics: Sterile

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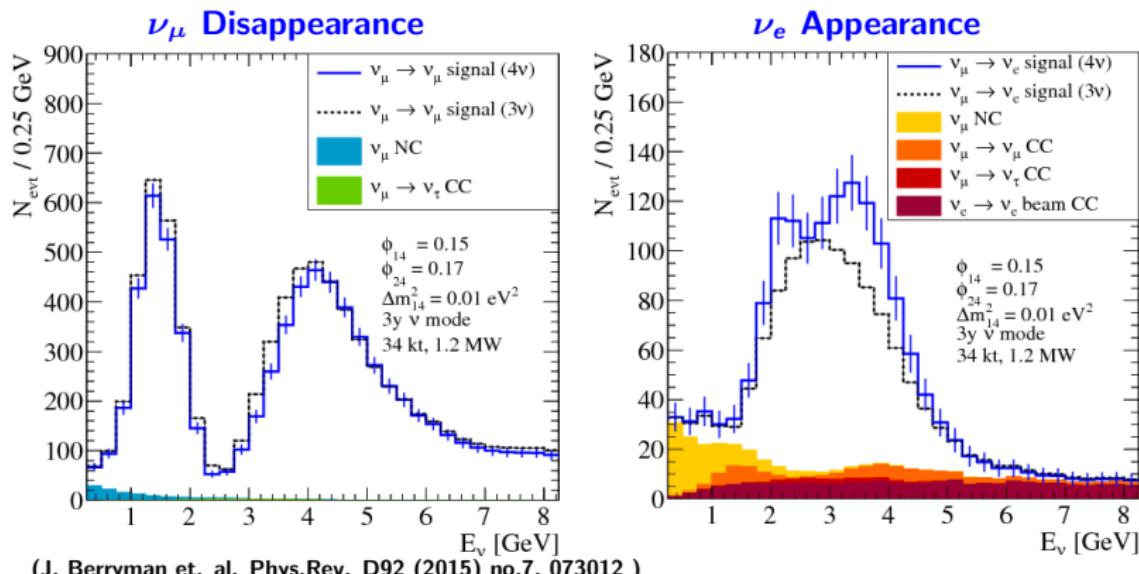
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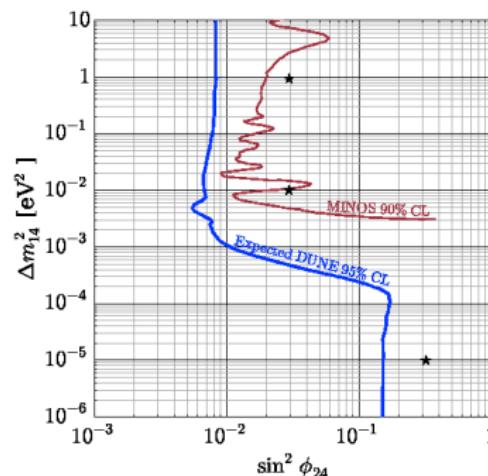
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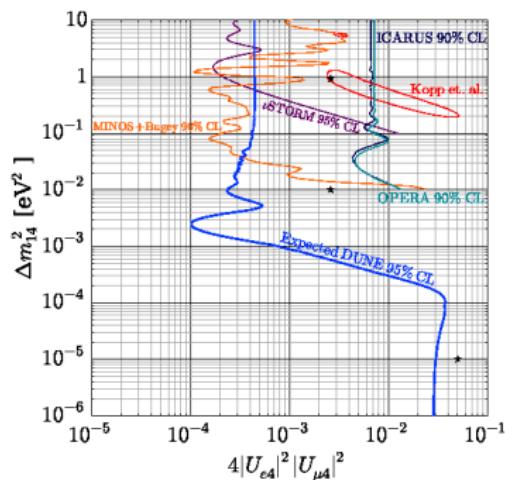
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ν_μ Disappearance



ν_e Appearance



(J. Berryman et. al. Phys.Rev. D92 (2015) no.7, 073012)

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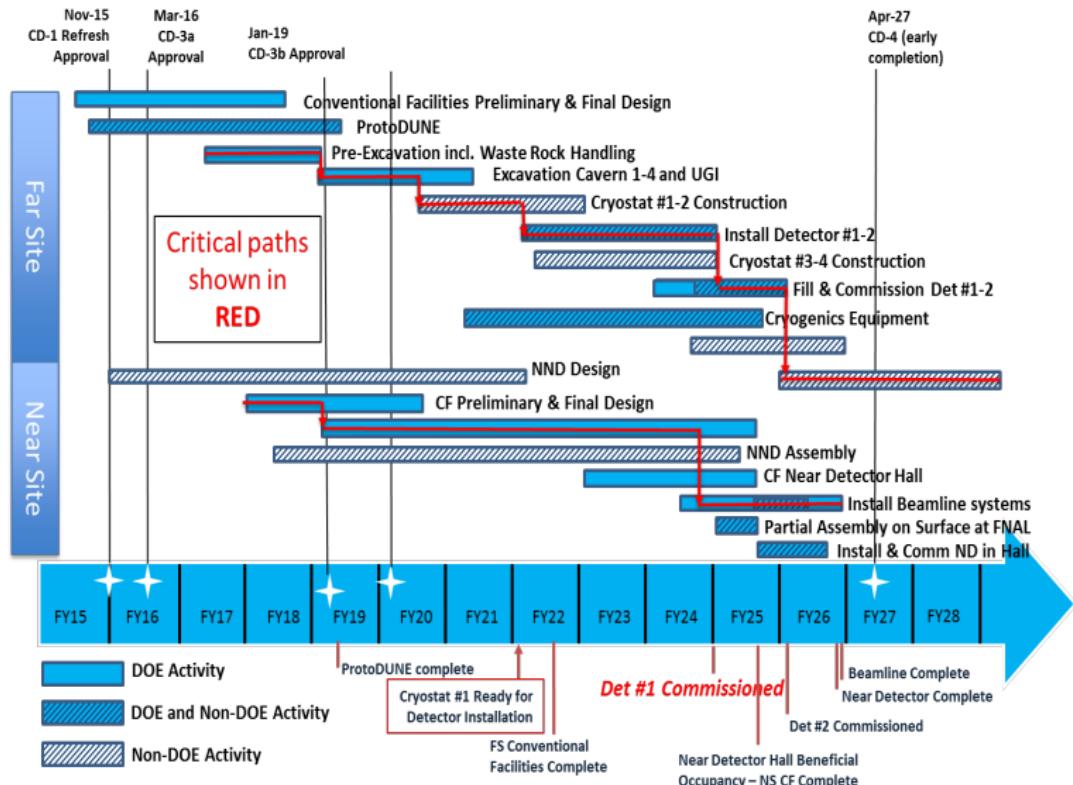
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Summary and Conclusions

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Conclusion

- Neutrino CP violation is best determined by studying $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations over long-baselines.
- Long-baseline experiments need to separate CP asymmetries from asymmetries induced by the expected MSW effect as well as new physics effects such as sterile neutrinos and NSI (if they exist).
- The current generation of experiments after a decade of running could rule out $\delta_{CP} = 0$ at 90% C.L. over a large fraction of $\delta_{CP} - \theta_{23}$ space. Combined results from running NO ν A and T2K at maximum power could produce evidence for CPV at 3σ if it is maximal by mid 2020's.

LBNF/DUNE can establish CPV at 5σ over a wide range of δ_{CP}
LBNF/DUNE can reach the same precision on θ_{13} as reactor experiments \Rightarrow unitarity tests.

Wide-band tunable beam can also access $\nu_\mu \rightarrow \nu_\tau$
AND possibly disentangle BSM effects such as CPV from ν_s , or NSI (studies ongoing).

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THANK YOU